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OBSERVATIONS OF MIDDLE AND LOWER CLOUD COMPOSITION DURING WINTER AND SPRING

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The meteorological importance of the state of the water particles in clouds was emphasized several years ago by the work of Bergeron [1] and Findeisen [2, 3] on the mechanism of precipitation. More recently the discovery by Schaefer [4] of a method of introducing dry-ice nuclei into water clouds, thus realizing the possibility of some control of precipitation which was recognized earlier by Findeisen, has again directed attention to the subject. Many American meteorologists considered Findeisen's arguments unconvincing, probably because he failed to present specific observational data to support them. Since the results of recent observations tend to confirm several important points in his discussion of cloud structure and precipitation, it is believed pertinent to bring up the subject again in order to present the results here, even though most of the ideas involved are not new. In this paper the principal middle and lower cloud types will be discussed with reference to whether they are ordinarily composed of ice particles or liquid water drops.

The program of ice-prevention research being conducted by the National Advisory Committee for Aeronautics at the Ames Aeronautical Laboratory has resulted in the accumulation of a considerable number of direct observations of cloud composition. A quantitative study of drop size and liquid water content in clouds has previously been presented as part of the results of this program [5]. In this paper the purpose is to present the results of qualitative observations of the state of the water particles of various types of clouds. The observations were made during the winter and spring seasons of 1945–46 and 1946–47. Although most of the flights were in the Pacific Northwest and the northern Plateau region, some data were also taken in the eastern United States. All of the observations included in this study were made at temperatures below freezing.

OBSERVATIONAL DATA

It was found that the presence or absence of ice crystals (or snow [2]) in the air can best be determined in flight by visual observation against a very dark background such as an opening in the nacelle. Against such a background the individual ice particles were seen as discrete streaks of light, while liquid cloud drops, being much smaller and more numerous, appear as a nebulous haze. This visual technique gave a positive means of distinguishing between liquid drops and ice crystals, evidenced by the fact that ice always formed on the thermometer strut, located just outside the observer's window, whenever the milky haze characteristic of liquid water clouds was seen in flight, and conversely, never formed in the absence of this haze, even when the light streaks characteristic of ice crystals were observed.

Another indication of the presence and approximate size of the ice crystals was obtained by means of a small piece of black sponge rubber. It was placed in the thermometer mounting bracket on the plane and located in such a position that an area about 0.5 cm. wide was exposed at right angles to the air stream. Individual ice crystals could be clearly seen as they struck this surface and remained motionless for a few seconds, before evaporating under the influence of dynamic heating. The average diameter of the particles thus observed was estimated at between 0.5 and 1 mm.

For the purpose of this study, the observations of cloud composition were divided into three categories: (*a*) Clouds composed entirely of liquid water drops or containing only an insignificant quantity of ice crystals; (*b*) Clouds composed entirely of ice crystals or containing an insignificant amount of liquid water; and (*c*) Clouds of mixed composition. The number of cases observed to fall in each category was tabulated for each of the principal cloud forms defined in the International Atlas [6]. The cloud forms were identified on the basis of visual observations made from the clear air outside the cloud masses. The results are presented in Table 1.

TABLE 1.—*Observations of the composition of clouds at temperatures below freezing*

Cloud type	Number of cases		
	Liquid drops	Ice crystals	Ice crystals and liquid drops
Middle clouds:			
Altostratus	3	27	7
Altocumulus	15	0	0
Low clouds:			
Stratocumulus	19	0	9
Stratus	4	0	1
Nimbostratus	1	4	1
Clouds with vertical development:			
Cumulus	21	0	5
Cumulonimbus	0	2	8

DISCUSSION

Altostratus clouds.—As the summary in Table 1 shows, a great majority of the altostratus clouds observed were composed almost entirely of ice crystals. This observed structure is consistent with the model of precipitating stratiform clouds proposed by Findeisen [2, 3] but refutes the opinions of many meteorologists in this country. In accepting the international definitions of cloud forms

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[2] The terms "ice crystals" and "snow" are here used interchangeably, since all but the smallest ice crystals in clouds are large enough to fall with an appreciable velocity. The distinction between cloud and precipitation particles, though valid for liquid drops, does not apply to ice crystals.

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[6], wherein altostratus clouds are distinguished from cirrostratus clouds by the absence of halos in the former, it is believed that these meteorologists have tacitly assumed that the absence of halos implies the absence of ice crystals. This, however, is not the case. Halos are formed only in clouds in which simple hexagonal prisms are the predominant crystal form, and are not observed in connection with hexagonal plates, capped columns, star-shaped forms, or other crystal types, as pointed out by Weickmann [7]. In flights within or over altostratus clouds, the frequent observation of a diffuse bright spot or streak below the sun, believed to be produced by diffuse reflection from a horizontal surface, has suggested that these clouds are usually composed predominantly of flat-plate-type crystals and that the most probable orientation of the plates is horizontal, or oscillating about the horizontal.

In order to illustrate the difference in physical characteristics of clouds composed of liquid drops and those composed of ice crystals, Table 2 has been prepared to show a hypothetical comparison between them when they have the same free water content. The value of 0.2 grams of free water per cubic meter was chosen as typical of middle clouds composed of liquid drops. The free water content of similar clouds composed of ice crystals has not been measured but is believed to be of the same order of magnitude. Data for liquid clouds were based mainly on the measurements made in the course of the N. A. C. A. icing research program [5]; data for ice crystal clouds were based mainly on the measurements of snow crystals reported by Schaefer [8]. The hexagonal-plate-type crystal was chosen as typical for altostratus clouds, and values of its dimensions were based on the data given by Schaefer. The outstanding difference between water and ice clouds is in the number and size of the particles, since the liquid water drops are about 10,000 times as numerous and $\frac{1}{10,000}$th as heavy as the ice crystals.

TABLE 2.—*A comparison of the physical characteristics of typical clouds of middle levels composed of (a) liquid water and (b) ice crystals, with the sources of information indicated*

Physical characteristics	Cloud composition			
	Liquid water		Ice crystals	
Free water content [1]	0.2 gm/m^3	(a)	0.2 gm/m^3	
Shape of average particle	sphere		hexagonal plate	
Diameter of average particle [1]	1.3×10^{-3} cm	(b)	6×10^{-2} cm	(c)
Thickness of average particle [1]			4×10^{-3} cm	(c)
Average projected area of particle [2] [3]	1.3×10^{-6} cm^2		2.0×10^{-3} cm^2	
Mass of average particle [2]	1.15×10^{-9} gm		1.4×10^{-5} gm	
Number of particles per cubic meter [2]	1.74×10^{8}		1.4×10^{4}	
Rate of fall of average particle	0.52 cm/sec	(d)	50 cm/sec	(c)
Distances of fall of average particle in air with 90 percent relative humidity.	0.006 m	(e)	100 m	(f)
Total projected area of particle per cubic meter [2]	231 cm^2		28 cm^2	
Visibility	195 m	(g)	1,610 m	(h)

[1] Assumed quantity.
[2] Calculated from assumed data.
[3] Random orientation of ice particles is assumed.
(a) From data by the author [5].
(b) Median of a number of cases, by the author.
(c) From data of Schaefer [8].
(d) From data of Simpson [11].
(e) From data of Findeisen, given by Simpson [11].
(f) One-third of distance used for drops of same mass.
(g) From Traubert's formula, given by Kampe [12].
(h) Determined by increasing the visibility for a cloud of liquid water in proportion to the total projected areas of the particles for the 2 types of clouds.

In the course of the flight program it was noted that the principal properties set forth by the International Atlas for defining altostratus clouds are characteristic of ice-crystal clouds. These are (*a*) striated or fibrous appearance; (*b*) sun or moon showing vaguely, with a gleam, as through ground glass; and (*c*) the absence of real relief on the lower surface of the cloud. That these properties are characteristic of ice-crystal clouds may be readily understood by reference to Table 2. The striated and fibrous appearance is due to the very considerable falling velocity, especially of the larger particles, which gives rise to many small streaks, resembling virga, in the base of the cloud. If vertical wind shear is present, as is the case when the cloud is formed above a frontal surface, these streaks are inclined from the vertical and may become nearly horizontal. The fact that the sun or moon can be seen vaguely through a relatively thick layer is due to the high visibility in ice-crystal clouds as compared with water-drop clouds with the same free water content. Humphreys [9] has shown that the optical effect of flat-plate crystals falling horizontally is the illumination of the sky at all distances from the sun out to 115 degrees, which accounts for the ground-glass appearance and whitish gleam also mentioned in the International Atlas as characteristic of altostratus clouds.

Because of their relatively large size, ice crystals can fall to considerable distances below the cloud base without evaporating, which gives rise to the diffuse lower boundary of the cloud mass described in the International Atlas. Drops which constitute water clouds, on the other hand, cannot fall below the cloud base without evaporating; hence, liquid clouds are ordinarily characterized by sharp bases showing real relief. Only in exceptional cases, when cloud drops approaching drizzle size (0.01 cm. or more in diameter) are present, may liquid clouds have diffuse bases.

Altocumulus clouds.—As shown by the data in Table 1, altocumulus clouds were found to be composed usually of liquid drops. According to the International Atlas, the features which distinguish a continuous sheet of altocumulus clouds from altostratus clouds are that the elements of altocumulus clouds show in real relief on the surface of the cloud, and that striated or fibrous structure is absent in them. As explained in the preceding section, these are characteristics of clouds composed of liquid drops.

Altocumulus clouds are often found on the lateral edges of middle cloud systems associated with depressions. They give way to altostratus as the central precipitation area is approached, and in this region of transition, the cloud forms containing both ice crystals and water drops occur. In this unstable state the water drops soon disappear, due to the difference between the vapor pressure over ice and that over water. Conditions of this kind may account for the seven cases of mixed composition classified as altostratus in Table 1. The three cases of liquid clouds classified in the table as altostratus are believed due to a mistake in the identification of the cloud type, a smooth altocumulus opacus being confused by the observer with altostratus.

Occasionally patches of altocumulus are observed near the top of large and very tenuous masses of altostratus. Findeisen [2, 3], in discussing this case, concluded that these liquid altocumulus clouds were formed in a region from which nearly all of the ice nuclei had already fallen as snowflakes.

Stratus and stratocumulus clouds.—Typical stratus and stratocumulus clouds were observed to be composed of liquid drops. There were also a number of cases of mixed composition, where conditions are unstable and therefore transient. As indicated in Table 1, they occur with considerable frequency. Light snow sometimes forms within these clouds, causing gradual dissipation of the cloud from the base upwards; this happens most frequently when the temperatures are below $-10°$ C. Snow also sometimes falls into stratocumulus layers from above, usually from an overlying layer of altostratus, causing rather rapid depletion of the liquid water in the cloud.

Nimbostratus clouds.—The name nimbostratus is usually applied to the lower portions of precipitating altostratus-type cloud systems. Such clouds would be expected to consist of ice crystals above the freezing level and a mixture of falling rain and liquid cloud droplets below the freezing level, with a mixture of liquid cloud drops and snowflakes just above the freezing level, as discussed by the author elsewhere [**10**].

The observed case of mixed composition at below-freezing temperature, classified as nimbostratus in Table 1, was a stratocumulus cloud in process of depletion after the onset of precipitation. The case of nimbostratus composed of liquid drops, listed in Table 1, was observed in a situation in which light, fine rain was produced from clouds composed entirely of liquid drops. In three winters' observations, the latter case was the only one in which liquid precipitation was found to form at temperatures below freezing. It occurred during the passage of a cold front in the vicinity of Seattle, Wash.

Cumulus and cumulonimbus clouds.—The observations listed in Table 1 are consistent with the generally accepted idea that the transformation from cumulus to cumulonimbus is brought about by the formation of ice crystals in the upper portion of the cloud. In the listing, the cases of clouds of mixed composition which were classified as cumulus rather than cumulonimbus were a result of the fact that the visible characteristics of cumulonimbus (noticeable softening of outlines and appearance of fibrous structure) do not appear immediately when the transformation into cumulonimbus first begins. The structure is first apparent only after ice crystals begin to predominate in certain parts of the cloud.

Conditions within cumulonimbus clouds are highly variable. Regions of high water content, composed almost entirely of liquid cloud droplets, often alternate with regions of heavy precipitation consisting of snow, graupel, and hail, in which liquid water is almost completely absent. Measurements of liquid water content during the transformation of a cumulus congestus cloud into cumulonimbus showed a decrease from 1.9 to 0.2 grams per cubic meter in less than 20 minutes, illustrating the extreme rapidity of the change.

CONCLUSIONS

The following conclusions regarding cloud composition are based upon observations of middle and lower clouds at temperatures below freezing during winter and spring:

1. Altostratus and nimbostratus clouds are usually composed of ice crystals.
2. Cumulus, altocumulus, stratocumulus, and stratus clouds are generally composed of liquid drops.
3. Cumulonimbus clouds and certain transitional cases of stratocumulus and altostratus clouds contain a mixture of ice crystals and liquid drops.

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